Nuclear Structure: from the Jefferson Lab point of view

presented by

Douglas W. Higinbotham
Jefferson Lab
Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons.

The \((e,e'p)\) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.
Two Nucleon Short Range Correlations

Learning about the Strong Short-Range Repulsive Force Between Nucleons

$\rho_o = 0.17 \text{ GeV/fermi}^3$

$\rho \approx 5\rho_o$

$\rho_o = 0.17 \text{ GeV/fermi}^3$

$2N\text{-SRC}$

Nucleons
Brookhaven EVA Collaboration Result


$^{12}\text{C}(p,2p+n)$ Reaction

$p_f = p_1 + p_2 - p_0$

$p_0$ = incident proton

$p_1$ and $p_2$ are detected

**Nuclear Structure**: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
Questions

- Do correlations explain the observed spectroscopic factors?
- What fraction of the momentum distribution is due to 2N-SRC?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?
Nuclear Structure: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
Review of Electro-production Kinematics

- $e - e' = w$
- $w^2 - q^2 = -Q^2$
- $x_B = Q^2/2mw$
- $e_m = w - T_p - T_r$
- $p_m = q - p$

\[
\frac{d^6 \sigma}{d\Omega_e d\Omega_p d\omega dp} = K \sigma_{ep} S(\vec{p}_m, \epsilon_m)
\]
CEBAF Large Acceptance Spectrometer

**Nuclear Structure**: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
The observed "scaling" means that the electrons probe the high-momentum nucleons in the 2N-SRC phase, and the scaling factors determine the per-nucleon probability of the 2N-SRC phase in nuclei with $A > 3$ relative to $^3\text{He}$.
Estimate of $^{12}$C 2N-SRC

Convert the $^3$He Ratios to a Deuteron Ratios

$$\frac{a_{2N}(^{12}C)}{a_{2N}(^3He)} \cdot \frac{a_{2N}(^3He)}{a_{2N}(D)} = 4.93 \pm 0.39$$

Calculate Percentage of Correlations in Deuterium Using a Deuteron Wave-Function

$$a_{2N}(D) = 0.041 \pm 0.008$$

$$a_{2N}(^{12}C) = 0.20 \pm 0.045$$

This includes all three isotopic compositions (pn, pp, or nn) for the 2N-SRC phase in $^{12}$C.
New CLAS A(e,e') Result


The probabilities for 3-nucleon SRC are smaller by one order of magnitude relative to the 2N SRC.

The observed “scaling” means that the electrons probe the high-momentum nucleons in the 3-nucleon phase, and the scaling factors determine the per-nucleon probability of the 3N-SRC phase in nuclei with A>3 relative to $^3$He.

Less than 1% of total.
From the \((e,e')\) and \((e,e'p)\) Measurements

- 80 +/- 5\% - single particles moving in an average potential
  - 60 – 70\% independent single particles in shell model potential
  - 10 – 20\% shell model long range correlations
- 20 +/- 5\% - two-nucleon short range correlations
- Less than 1\% multi-nucleon corrections
  

**Coming Soon**: Hall C will be providing \(^2\text{H}, ^3\text{He}, ^4\text{He}\) \((e,e')\) \(x>1\) cross sections for absolute comparisons.

**Nuclear Structure**: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
Jefferson Lab's Hall A

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Jefferson Lab's Hall A
E89-044 $^3$He(e,e'p)d Results

- $x_B = 1$
- fixed ($q, w$) kinematics
- $Q^2 = 1.5 \text{ [GeV/c]}^2$
- low $p_m$ PWIA works
- medium $p_m$ FSI
- high $p_m$ multiple effects


**Nuclear Structure**: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
E89-044 $^3$He(e,e'p)pn Results


Nuclear Structure: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
"A full investigation of two-nucleon correlations would require (e,e'NN) coincidence studies, but these are technically not yet feasible."

Rolf Ent's Ph.D. Thesis 1989
Custom Experiment To Study Nucleon Pairs

\[ Q^2 = 2 \text{ [GeV/c]}^2, \ x = 1.2, \ p_m = 200 - 650 \text{ MeV/c}, \ E_{2m} < 140 \text{ MeV} \]

Luminosity of \(10^{37} \text{ cm}^{-2} \text{ s}^{-1}\)

A pair with “large” relative momentum between the nucleons and small CM momentum

- high \(Q^2\) minimizes MEC which are reduced as \(1/Q^2\)
- \(x > 1\) to suppress isobar contributions
- anti-parallel kinematics to suppress FSI

_Nuclear Structure_: Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
New Equipment for the Experimental Setup

- New Scattering Chamber
- New BigBite Hadron Spectrometer (100 msr)
- New Low Energy Neutron Detector
BigBite Spectrometer During SRC Experiment

**Nuclear Structure:** Spectroscopic Factors, Correlations, High Momentum Components, and the Coulomb Sum Rule
$^{12}\text{C}(e,e'\text{pp})$  Ran Shneor (Tel Aviv University)

- Operated at a luminosity of up to $10^{38}$ cm$^{-2}$ s$^{-1}$
- $\Delta E/E$ Particle Identification
- Timing Resolution of 0.4 ns
- Momentum Resolution $dp/p$ of 2% from time of flight

With acceptance corrections, the physics ratio of $(e,e'\text{pp})/(e,e'\text{p})$ is approximately 8%.

Ratio of detected recoiling protons.
Deuterium was used to determine the absolute neutron detection efficiency. After making efficiency and acceptance corrections, we find far more recoiling neutrons than protons.
From the (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short range correlations
  - from (e,e'pp) approx. 1% pp SRC
  - exact ratio for (e,e'pn) / (e,e'pp) not final, but preliminary result gives approx. 18% pn SRC
  - combining preliminary results we can deduce approx. 1% nn SRC
- less than 1% multi-nucleon correlations
The aforementioned experiments used exclusive reactions and/or extreme kinematics, now let's consider a sum rule.
Coulomb Sum Rule

- The sum rule states that the integration of the charge response of a nucleus over the full energy loss should equal the total charge of the nucleus.

\[ S_L(q) = \int_{\omega_{\text{el}}^-}^{\infty} d\omega \frac{R_L(q, \omega)}{Z \tilde{G}_E^2(Q^2)} \]

\[ \tilde{G}_E^2(Q^2) = \left( [G_E^p(Q^2)]^2 + (N/Z)[G_E^n(Q^2)]^2 \right) \frac{1 + Q^2/4M^2}{1 + Q^2/2M^2} \]

\[ \frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[ \frac{Q^4}{q^4} R_L(q, \omega) + \frac{Q^2}{2q^2} \frac{1}{\varepsilon} R_T(q, \omega) \right] \]

\[ \varepsilon = \left[ 1 + \frac{2q^2}{Q^2} \tan^2 \frac{\psi}{2} \right]^{-1} \]
Previous Results

- For the past twenty years, a large experimental program
- Limited kinematic coverage in \((q, \omega)\) due to technical limitations
Coulomb Sum Rule

- Saturation of the Coulomb Sum
  - $S_L(q) \rightarrow 1$ at sufficiently large $q$

- Deviation of the Coulomb Sum
  - at small $q$
    - Pauli blocking
    - Nucleon-nucleon long-range correlations
  - at large $q$
    - Short range correlations
    - Modification of the free nucleon electromagnetic properties inside the nuclear medium

- Coulomb Corrections Are Important

- One of the long lasting questions in physics
Jefferson Lab will measure $^4\text{He}$, $^{12}\text{C}$, $^{56}\text{Fe}$, $^{208}\text{Pb}$
Summary

- Using the now standard Jefferson Lab equipment is providing precision data in ideal kinematics.
- Understanding nucleon-nucleon correlations was part of the original motivation for building CEBAF.
- Adding new systems, such as the BigBite Spectrometer, are opening new research possibilities including making high luminosity measurements of (e,e'pN) possible.
- Many more experiments to come! Including $^{208}\text{Pb}(e,e'p)$ to study relativistic effects as well as long range correlations.
\( ^{208}\text{Pb}(e,e'p) \) Experiment Coming In 2007

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